Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

EFFECT OF SOME ROUGHING PARAMETERS ON GRAIN SIZE OF A MICROALLOYED STEEL

M.J. GODDEN and L. SETO
METALLURGY SECTION

FEBRUARY 1983

...(CANMET)

...énergie (CANMET)

ENERGY RESEARCH PROGRAM

PHYSICAL METALLURGY RESEARCH LABORATORIES
REPORT: ERP/PMRL 83-4(TR)

21 pp

SJV

PHYSICAL METALLURGICAL RESEARCH LABORATORIES
REPORT ERP/PMRL 83-4(TR)

EFFECT OF SOME ROUGHING PARAMETERS ON GRAIN SIZE OF A MICROALLOYED STEEL

by

M.J. Godden and L. Seto

ABSTRACT

The recrystallization of austenite during roughing has been studied in a 0.06% Nb, 0.1% C steel by quenching samples from selected stages of five different roughing schedules. All roughing schedules produced partial recrystallization in a single pass and complete recrystallization was produced by strain accumulation of repeated passes.

LABORATOIRES DE RECHERCHE EN MÉTALLURGIE PHYSIQUE
RAPPORT ERP/PMRL 83-4(TR)

LES EFFETS DE CERTAINS PARAMÈTRES DE DÉGROSSISSAGE SUR LA GROSSEUR DU GRAIN D'UN ACIER MICROALLIÉ

par

M.J. Godden et L. Seto

RÉSUMÉ

On a étudié la recristallisation de l'austénite durant le dégrossissage d'un acier de 0,06% Nb et 0,1% C en soumettant des échantillons du trempage à partir d'étapes sélectionnées de cinq schémas de travail de dégrossissage différents.

Il ont tous produit une recristallisation partielle lors d'une seule passe, et la recristallisation totale s'est produite par la déformation accumulée provenant de passes répéteés.

INTRODUCTION

Many factors can affect the strength and low temperature toughness of a given steel. Grain refinement can have a beneficial effect on both properties and is the most economical route to follow if improved toughness and strength are required. This technique is employed in the controlled rolling of HSLA steels. Grain size control is accomplished by increasing the density of ferrite nucleation sites through the production of pancaked unrecrystallized austenite grains and through control of the austenite to ferrite transformation. Thus an understanding of ferrite nucleation site production during the hot deformation of this class of steels is vital to the control and optimization of their properties.

Controlled rolling of HSLA steels can conveniently be divided into two regimes; roughing, in which the as-reheated grains are repeatedly recrystallized to the finest equiaxed grains possible; and finish rolling, in which the fine equiaxed grains are prevented from recrystallizing and the maximum number of ferrite nucleation sites are produced. In commercial practice, because a number of factors affect the choice of rolling schedule, a clear distinction between roughing and finish rolling is lost and optimum grain refinement and ferrite nucleation site production are not achieved. A knowledge of grain refinement processes during roughing is necessary before any rigorous study of ferrite nucleation site production can be made.

Over the past several years, the process of grain recrystallization during hot rolling has been studied on a number of occasions (1-6) and other workers have focused attention on ferrite nucleation site production (7,8). Much of this work has been done on small samples with carefully controlled temperature and uniform strain. The application of some of these results and models to roughing schedules comparable to those used in industry is the purpose of the work in this report. To this end, a series of roughing schedules was designed to test some current theories. Ingots were rolled to selected end points in a roughing schedule, were quenched, and the austenite grain size examined. Although HSLA steels generally have insufficient hardenability for quenching to martensite or bainite in thick sections these microstructures were considered necessary to reveal prior-austenite grain size. Thus, two steps were taken to increase the probability of low temperature transformation products upon quenching; a carbon content higher than usual for current HSLA

steels was chosen (0.095% C), and the ingot width was reduced. Also the different roughing schedules and a standard finish rolling schedule were used to produce 12.7 mm thick plate to ascertain if the differences observed during roughing were apparent in the final plate microstructure.

EXPERIMENTAL METHOD

Two 150 kg heats of similar composition were made at PMRL and each heat was cast into four equal-sized ingots; the analysis for each ingot is given in Table I. The ingots were slightly tapered, being approximately 230 mm long x 153 mm wide x 127 mm thick in the through-thickness direction. Each ingot was halved in width then it was ground in such a way that it tapered for half its length from 114 mm or more to 127 mm and was of a constant thickness of 127 mm for the remainder of its length. The ingots were prepared prior to rolling by chamfering both ends and placing thermocouples in holes at the mid- and quarter-thickness points to a depth of half the width. The ingots were rolled according to the schedules shown in Table 2. In each schedule, one ingot was quenched after the first pass, a second ingot was quenched after the completion of the roughing schedule and a third was rolled to 12.7 mm thick plate using a standard finish-rolling schedule and air cooled. When pieces were to be quenched, a 10s pause was adopted from exit at the rolls to the quench in iced brine. The austenite grain size after reheating prior to rolling was determined on 12 mm diam x 19 mm long cylinders machined from the cropped end of ingot 423-1. These cylinders were placed in holes drilled in a dummy billet at the quarter and mid-thickness positions. The dummy billet was placed in the furnace along with the other ingots and the cylinders were extracted from the holes for quenching. The mid-thickness thermocouple in the ingot was used for process control during rolling.

Samples for metallography were cut from the mid-thickness position in each rolled piece from a point adjacent to the thermocouple. The prepared surface of these samples and those of the small cylinders, as well, was in the rolling direction. The prior-austenite grain size of the quenched samples was revealed by etching at a temperature of 40-50°C in a solution of 100 ml saturated aqueous picric acid and 2 ml sodium tridecyl benzene sulphonate, 6 drops of HCl or 1 g $CuCl_2$. The as-rolled plate was etched in 2% nital. Grain size measurements were made manually on the quenched samples by the 3 circle

intercept method according to ASTM E112-77. The microstructures of the quenched samples were a mixture of martensite and bainite. Difficulty was encountered in revealing the prior-austenite grain boundaries. Frequently, regions of poorly-etched grain boundaries had to be drawn in on micrographs for clarity before measurements were made. On two samples, no success was achieved in revealing grain boundaries with either version of the etchant. Measurements of mean ferrite grain size and mean pearlite band spacing for the centre half of the finished plate were made with a Cambridge Instruments System 900 image analysing computer.

RESULTS

Measured mean prior-austenite grain sizes are summarized in Table 3. It can be seen that for both reheat temperatures there is a significant difference in mean grain size of the cylinders between the two locations where they were placed in the dummy billet. The grain size after the first pass of schedule 1 may also be taken as representative of the first pass of schedule 3 because the reductions are the same. There were very similar reductions in the first pass for schedules 2 and 4, which is reflected in the similar resultant grain sizes. It should be noted that all schedules resulted in a finer mean grain size after the first pass than existed after reheating (schedule 5 could be an exception which is discussed later). Furthermore, the greater reductions of schedules 2 and 4 gave greater grain refinement than those of schedules 1 and 3. However, at the termination of roughing, all the samples had a similar mean grain size, regardless of schedule. This is reflected in only minor differences in band spacing and mean ferrite grain size measured in the final plates (Table 4). However, consideration of mean grain size alone may lead to other differences between samples being missed, grain size distribution being particularly relevant.

Cylinders reheated to 1150°C showed a mixed grain size, some grains having grown considerably (Fig. 1). Unfortunately, it is not possible to quantify this effect on the image analysing computer because the etchant does not reveal the grain boundaries sharply enough and there is a lot of background contrast within the prior-austenite grains. The grain size variation seen in Fig. 1 could account for some of the differences in mean grain size measured between the two locations in the dummy billet. Considerable grain

size variation was observed in the sample quenched after the first pass of schedules 1 and 3 (Fig. 2), indicating that whereas the mean prior-austenite grain size was smaller than after reheating, not all grains had recrystallized.

The grain refinement experienced throughout schedule 2 is illustrated in Fig. 3. The reheated grain size (Fig. 3a) is more uniform than in the previous two figures. The grain size distribution after the first pass (Fig. 3b) again shows evidence of some large unrecrystallized grains. However, there are fewer large grains than in Fig. 2, which could account for the smaller mean grain size following the first pass. A few of the larger grains are seen to be elongated in the rolling direction at the end of roughing (Fig. 3c). This phenomenon was observed for all schedules but was particularly noticeable for schedules 2 and 3, these having had the greatest reduction at 1040°C.

Finally, it should be noted that the mean pearlite band spacing (Table 4) is slightly larger than the prior-austenite grain size at the completion of roughing.

DISCUSSION

Any interpretation of microstructural change during rolling requires a knowledge of the prevailing temperatures and the mode of deformation. All samples were taken from material adjacent to the thermocouple located at the mid-thickness. Because this thermocouple was also the process control thermocouple, the thermal history of the microstructure measured is known. However the deformation history is much less precise. It is well known that deformation during rolling is inhomogeneous, varying with plate depth, roll friction forces, amount of deformation and other factors (see for example, Schey (9)). Furthermore, the device of reducing the ingot width to increase the cooling rate, important when the piece to be quenched is thick, results in deformation which is not plane strain at the centre of the piece. Plane strain at mid-width is applied during the commercial rolling of wide plate. Hence, while the reduction in ingot/plate thickness is known, the precise strain produced at the mid-thickness, where the metallographic sample was taken, is unknown but is probably less than the nominal strain.

After reheating, the austenite grain size is determined by the time and temperature of reheating and the presence of second phase particles, in

this case NbC or NbN. Several workers (10-14) have determined the solubility products of NbC and NbN. All give different temperatures at which the NbC or the NbN is completely dissolved, and thus, rapid grain growth can occur. For example, using the formula developed by Narita (10) with the average carbon and niobium contents for all the ingots (Table 1), indicates that NbC would be completely dissolved at 1126°C. Although nitrogen analyses were not done, typical PMRL foundry practice produces nitrogen levels of 0.009% maximum; at this value, all the NbN would be in solution by 1129°C. However, such formulae should be used with caution because (a) they assume thermodynamic equilibrium which is unlikely to be achieved, and (b) the solubility limits are affected by other alloying elements; for example, the high manganese content would significantly increase the NbC and NbN solubility. Nevertheless, the small austenite grain size after reheating to 1150°C suggests that the solubility limit has barely been reached. The observed austenite grain size may be compared with that obtained by Amin and Pickering (6) who measured a grain size of 57 μm after 1/2 h at 1150°C and a grain size of 150 μm after 1/2 h at 1230°C in a steel containing 0.07% Nb and 0.09%C. Even at 1230°C, our austenite grain size is quite small compared with ~300 μm frequently obtained on heating steels of lower carbon and niobium content. For example, in earlier work, Godden et al (15) measured a grain size of 270 μm after reheating a 0.067%C, 0.048% Nb, 0.3% Mo, 1.95% Mn steel to 1230°C. In practical terms, this means that the total grain refinement possible in these current steels is limited, particularly after 1150°C reheat, given the observation of Cuddy (3,4) that roughing cannot be expected to refine the austenite grain size to less than 15-20 μm.

The prior-austenite grain size observed in samples quenched during the rolling schedule is the net result of the deformation, recrystallization or recovery and subsequent grain growth. Static rather than dynamic recrystallization occurs at the temperatures and deformations used in this work (5). Depending on temperature, grain growth can occur after recrystallization (1). A pause of 10s was chosen to ensure all specimens were in the same condition upon quenching. However, specimen bulk increased the time and hence, reduced the severity of the quench. Kozasu et al (1) observed that, in a 0.03% Nb steel at 1200°C, the grain size was 52 μm after 3s, 68 μm after 20s and 119 μm after 300s, whereas at 1050°C the grain size was 25 μm after 3s, 26 μm after 30s and 32 μm after 300s. If we assume a total delay after re-

crystallization of 20-30s, there is likely some grain growth in specimens quenched after the first roughing pass at 1150°C. The amount of grain growth is hard to assess but might be as much as 25% if the lower temperature (1150° of 1200°C) and higher niobium content are taken into account. Certainly the grain growth for the specimens quenched at the end of roughing at 1040°C is likely to be so small as to be undetectable.

The temperature regimes for full recrystallization, partial recrystallization and recovery have been shown to be dependent upon the initial grain size, amount of strain and steel composition (1,2,3). Studies (1,2) have shown that a minimum temperature of 1220°C is needed if a 0.03% Nb steel is to fully recrystallize as a result of the amount of deformation from pass 1 of schedule 2 (the severest deformation in the first pass). The high niobium content of our steels likely raises this temperature further. Hence, all samples show only partial recrystallization after the first pass; although, because of the smaller deformation, schedules 1 and 3 show more unrecrystallized grains than schedules 2 and 4. It had been hoped that the formula developed by Machida et al (16) relating initial and final grain sizes to the amount and speed of deformation could be tested. However, at no time did full recrystallization occur and thus, the formula is not applicable. It is notable that even the small deformations applied in the first pass of schedules 1 and 3 did not result in the grain growth that was seen in earlier work (15). It is quite possible that grain growth did occur in the first pass of schedule 5, however.

The unrecrystallized grains seen after the first pass did recrystallize before the completion of roughing (compare Figs. 3b and 3c). This is interpreted as meaning that total recovery did not occur during the interpass time of 10-20s, permitting strain to accumulate in the unrecrystallized grains which led to their eventual recrystallization in subsequent passes. Recrystallization caused in this manner has not been thoroughly studied in other work, where reductions of 20-70% are more normally applied and repeated deformation is less common. Furthermore, this phenomenon is contrary to the generally held view (2,5,17) that subsequent deformations of a partially recrystallized structure cause recrystallization of only those fine grains already recrystallized; the large unrecrystallized grains remain to give a duplex final plate grain size. This is important for industrial practice where often small reductions (<10%) are applied because of limited mill power and the need to cool as quickly as possible from a high reheat temperature.

As the temperature decreases throughout the roughing schedule, the deformation needed to cause recrystallization increases. This is counteracted to some extent by strain accumulation (less that due to recovery) with each pass, but clearly, fewer grains recrystallize as the temperature decreases. Consequently, the schedules with large reductions at low temperatures showed the most elongated (unrecrystallized) grains i.e. schedules 2 and 3 (again schedule 5 will be discussed later).

Schedules 1 to 4 all showed similar grain size (~23 μm) at the completion of roughing. This value is slightly larger than the 15-20 μm suggested by Cuddy (3,4) as being the ultimate currently attainable. There are two possible explanations for the samples attaining similar grain sizes despite different roughing schedules. The first possibility is that the ultimate grain size has been reached, although this is larger than reported by Cuddy. The second possibility is that the final grain size is related to a parameter that remained invariant throughout schedules 1 to 4. This parameter seems most likely to be the total strain incurred by roughing, given the previously-noted importance of strain accumulation in recrystallization. The difference in ultimate grain size compared with that reported by Cuddy gives credibility to this notion.

It is not possible to relate the final plate band spacing to anything observed earlier in the rolling schedule. The band spacing is larger than the austenite grain size at the completion of roughing. It is therefore much larger than the grain size in the through-thickness direction after the considerable pancaking that occurs in finish rolling has taken place (82% reduction).

One can only speculate on what happened during schedule 5 because of the lack of results. The as-rolled plate microstructure is similar to that seen in schedules 1 to 4 (Table 4). We concluded that it probably produced the same grain size as the other schedules on completion of roughing, because all schedules had the same finish rolling treatment. If this is so, the grain refinement that occurred in schedule 5 was less than occurred in schedules 1 to 4 despite the same reduction being applied in each schedule. A possible explanation could be that the first few passes (which are small reductions) caused grain growth rather than grain refinement, so that after a few passes, schedules 1, 3 and 5 had similar grain size. Alternatively, the lower temperature regime for roughing in schedule 5 could have meant there was less deformation at a temperature at which recrystallization could occur. This

As the temperature decreases throughout the roughing schedule, the deformation needed to cause recrystallization increases. This is counteracted to some extent by strain accumulation (less that due to recovery) with each pass, but clearly, fewer grains recrystallize as the temperature decreases. Consequently, the schedules with large reductions at low temperatures showed the most elongated (unrecrystallized) grains i.e. schedules 2 and 3 (again schedule 5 will be discussed later).

Schedules 1 to 4 all showed similar grain size (~23 μm) at the completion of roughing. This value is slightly larger than the 15-20 μm suggested by Cuddy (3,4) as being the ultimate currently attainable. There are two possible explanations for the samples attaining similar grain sizes despite different roughing schedules. The first possibility is that the ultimate grain size has been reached, although this is larger than reported by Cuddy. The second possibility is that the final grain size is related to a parameter that remained invariant throughout schedules 1 to 4. This parameter seems most likely to be the total strain incurred by roughing, given the previously-noted importance of strain accumulation in recrystallization. The difference in ultimate grain size compared with that reported by Cuddy gives credibility to this notion.

It is not possible to relate the final plate band spacing to anything observed earlier in the rolling schedule. The band spacing is larger than the austenite grain size at the completion of roughing. It is therefore much larger than the grain size in the through-thickness direction after the considerable pancaking that occurs in finish rolling has taken place (82% reduction).

One can only speculate on what happened during schedule 5 because of the lack of results. The as-rolled plate microstructure is similar to that seen in schedules 1 to 4 (Table 4). We concluded that it probably produced the same grain size as the other schedules on completion of roughing, because all schedules had the same finish rolling treatment. If this is so, the grain refinement that occurred in schedule 5 was less than occurred in schedules 1 to 4 despite the same reduction being applied in each schedule. A possible explanation could be that the first few passes (which are small reductions) caused grain growth rather than grain refinement, so that after a few passes, schedules 1, 3 and 5 had similar grain size. Alternatively, the lower temperature regime for roughing in schedule 5 could have meant there was less deformation at a temperature at which recrystallization could occur. This

would mean more severe pancaking than for the other schedules but the accompanying increase in nucleation site density may have been too small to be detectable.

CONCLUSIONS

1. Grain growth was not seen after light reductions.
2. All roughing schedules produced partial recrystallization at all temperatures and reductions. However, grains not recrystallized after one pass can accumulate some strain, resulting in recrystallization before the completion of roughing.
3. All roughing schedules produced a similar grain size of ~23 μm at the completion of roughing. This could be the result of all schedules having the same total strain rather than an ultimate grain size, proposed by other workers, having been reached.
4. The lower reheat temperature of schedule 5 did not produce any significant refinement of the final plate microstructure.
5. The final plate pearlite band spacing does not appear to be related to the austenite grain size observed during rolling.
6. No evidence was seen to support the contention of other workers that a partially recrystallized structure always recrystallizes in previously recrystallized regions while large unrecrystallized grains remain unrecrystallized at the completion of roughing, resulting in a final plate duplex grain size.

ACKNOWLEDGEMENTS

The authors are indebted to PMRL foundry staff for making the steels, Dr. G. Ruddle and staff of the Metal Forming section for their cooperation in rolling the steels and Dr. M. Shehata and B. Casault for measurements made on the image analysing computer.

REFERENCES

1. Kozasu, I., Ouchi, C., Sampei, T. and Okita, T. "Microalloying 1975"; Conference Proceedings; Published by Union Carbide Corp., 126-128; Washington; Oct. 1975.

2. Sekine, H., Maruyama, T., Kageyama, H. and Kawashima, Y. "Thermochemical processsing of microalloyed austenite"; Conference Proceedings; 141-142; Published by A.I.M.E.; Eds. A.J. DeArdo, G.A. Ratz and P.J. Wray; Pittsburgh; Aug. 1981.

3. Cuddy, L.J. ibid 129-140.

4. Cuddy, L.J. Met Trans, 12A 1313-20; (1981).

5. Katsumata, H., Machida, M. and Kaji, H. "Thermomechanical processing of microalloyed austenite"; Conference Proceedings; 101-119; Published by A.I.M.E.; Eds. A.J. DeArdo, G.A. Ratz and P.J. Wray, Pittsburgh; Aug. 1981.

6. Amin, R.K. and Pickering, F.B. ibid 1-31.

7. Roberts, W. Scand. J Metallurgy 9 13-20; (1980).

8. Roberts, W., Lidefelt, H. and Sandberg, A. "Hot working and forming processes"; Conference Proceedings, Published by The Metals Society; Eds. C.M. Sellars and G.J. Davies; 38-42; Sheffield 19; 1980.

9. "Metal deformation processes: friction and lubrication"; Ed. J.A. Schey, published by Marcel Dekker Inc.; 1970.

10. Narita, K. Trans I.S.I.J. 15, 145-52; (1975).

11. Aronsson, B. "Steel-strengthening mechanisms"; Symposium Proceedings; Published by Climax Molybdenum Corp.; 77-88, Zurich; May 1969.

12. Hudd, R.C., Jones, A. and Kale, M.N. J.I.S.I. 209, 121-25; (1971).

13. Irvine, K.J., Pickering, F.B. and Gladman, T. J.I.S.I. 205, 161-82; (1967).

14. Keown, S.R. and Wilson, W.G. "Thermomechanical processing of microalloyed austenite"; Conference Proceedings; Published by A.I.M.E., 343-59; Eds. A.J. DeArdc, G.A. Ratz and P.J. Wray, Pittsburgh; Aug. 1981.

15. Godden, M.J., Ruddle, G.E., Crawley, A.F. and Boyd, J.D. ibid, 253-266.

16. Machida, M., Katsumata, M. and Kaji, H. Trans I.S.I.J. 20, B616; (1980).

17. Tanaka, T., Enami,T., Kimura, M., Saito, Y. and Hatomura, T. "Thermomechanical processing of microalloyed austenite"; Conference Proceedings; Published by A.I.M.E. 195-216; Eds. A.J. DeArdo, G.A. Ratz and P.J. Wray, Pittsburgh; Aug. 1981.

Table 1 - Ingot compositions

Ingot number	Weight %										
	C	Mn	Nb	Ni	Cr	Mo	V	Si	S	P	Al
414-1	0.10	1.50	0.06	<.01	<.015	<.01	<.005	0.30	<.002	<.002	.035
414-2	0.095	1.49	0.06	<.01	<.015	<.01	<.005	0.30	<.002	<.002	.030
414-3	0.095	1.49	0.06	<.01	<.015	<.01	<.005	0.30	<.002	<.002	.030
414-4	0.105	1.50	0.06	<.01	<.015	<.01	<.005	0.30	<.002	<.002	.030
423-1	0.10	1.52	0.065	<.01	<.015	<.01	<.005	0.29	.003	.004	.035
423-2	0.090	1.51	0.06	<.01	<.015	<.01	<.005	0.29	.002	.004	.035
423-3	0.10	1.50	0.06	<.01	<.015	<.01	<.005	0.28	.003	.004	.030
423-4	0.095	1.47	0.06	<.01	<.015	<.01	<.005	0.28	.003	.004	.030

Table 2 - Rolling schedules

Pass Number	Schedule 1		Schedule 2		Schedule 3		Schedule 4		Schedule 5	
	Roll gap mm	Temp. °C	Roll gap mm	Temp. °C	Roll gap mm	Temp. °C	Roll gap mm	Temp. °C	Roll gap mm	Temp. °C
1	117	1150	108	1150	117	1150	109	1150	117	1100
2	108	1135	91	1110	108	1135	99	1120	108	1090
3	99	1120	76	1075	99	1120	91	1105	99	1075
4	91	1105	63.5	1040	91	1105	84	1090	91	1060
5	84	1090			85	1090	76	1075	84	1045
6	76	1075			80	1075	70	1060	76	1030
7	70	1060			63.5	1040	63.5	1040	70	1015
8	63.5	1040							63.5	990

Finish rolling schedule used for all above roughing schedules:

Roll gap mm	Temp °C
55	900
46	885
37	870
29	855
23	835
16.5	815
11.7	790

All ingots soaked 1 hour at 1230°C except those of schedule 5 which were soaked 1 hour at 1150°C.

Table 3 - Grain sizes measured after reheating and after different stages of the rolling schedules

Grain size in mm (limits are 95% confidence)

Schedule number	1	2	3	4	5
After Soaking	←	1/2 thickness 0.170 ± 0.010 1/4 thickness 0.130 ± 0.007	→	→	1/2 thickness 0.067 ± 0.003 1/4 thickness 0.032 ± 0.001
After First Pass	0.082 ± 0.006	0.064 ± 0.004		0.061 ± 0.005	Unable to measure grain size
After Roughing (i.e., 63.5 mm)	0.023 ± 0.002	0.022 ± 0.002	0.025 ± 0.002	0.025 ± 0.003	Unable to measure grain size

Table 4 - Measurements on final plate microstructure

Schedule number	*Mean band spacing μm	Mean ferrite grain size μm	Polygonal ferrite %
1	40 ± 8	3.9 ± 0.2	82 ± 1
2	32 ± 6	3.8 ± 0.1	80 ± 1
3	37 ± 6	4.2 ± 0.2	85 ± 1
4	30 ± 5	3.9 ± 0.2	82 ± 1
5	28 ± 5	4.2 ± 0.2	83 ± 1

*Measured between 1/4 and 3/4 thickness. Band spacings of more than 300 bands measured for each sample.

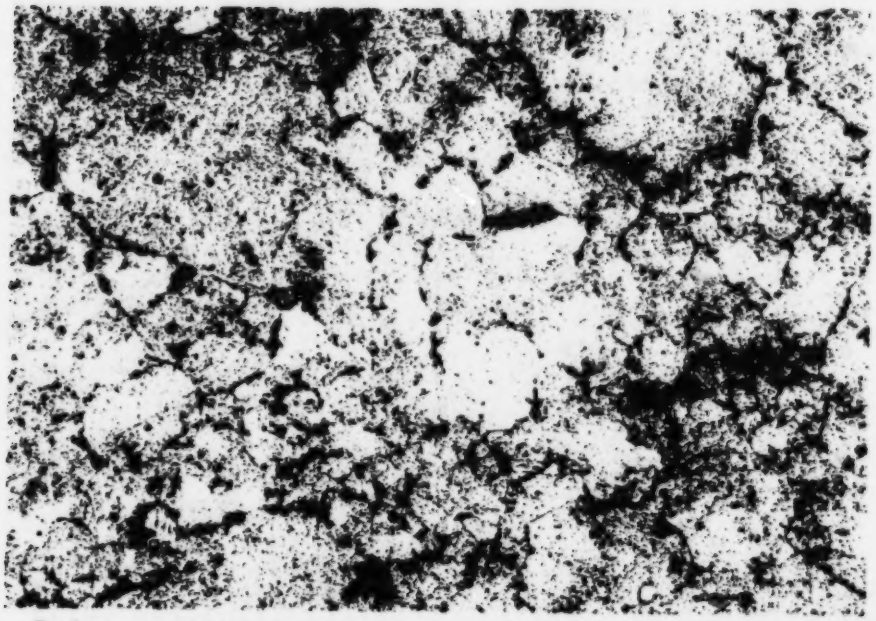


Fig. 1. Prior austenite grains in cylinder heated to 1150°C for 1 h in centre of dummy billet. Note some grains have grown considerably. X100. (neg 7755)

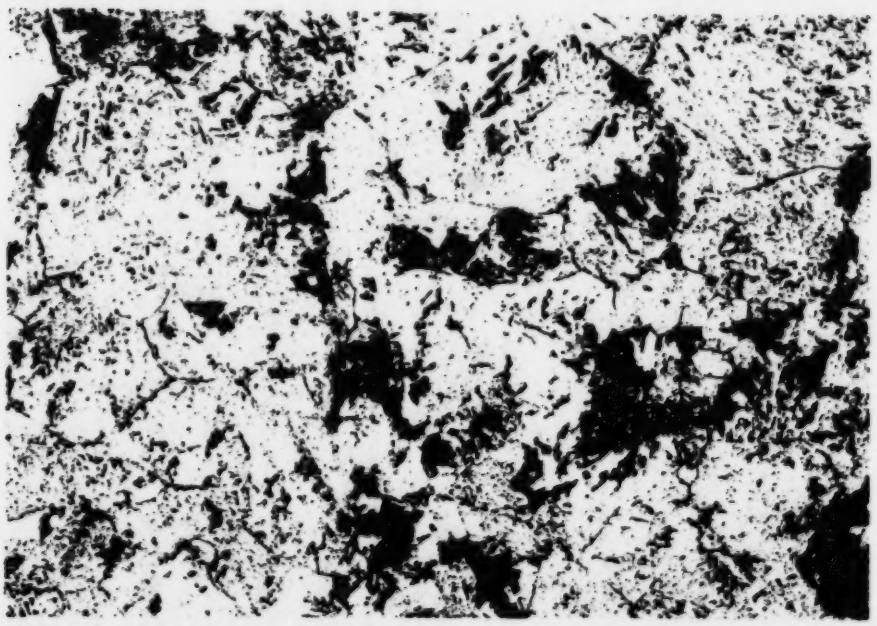
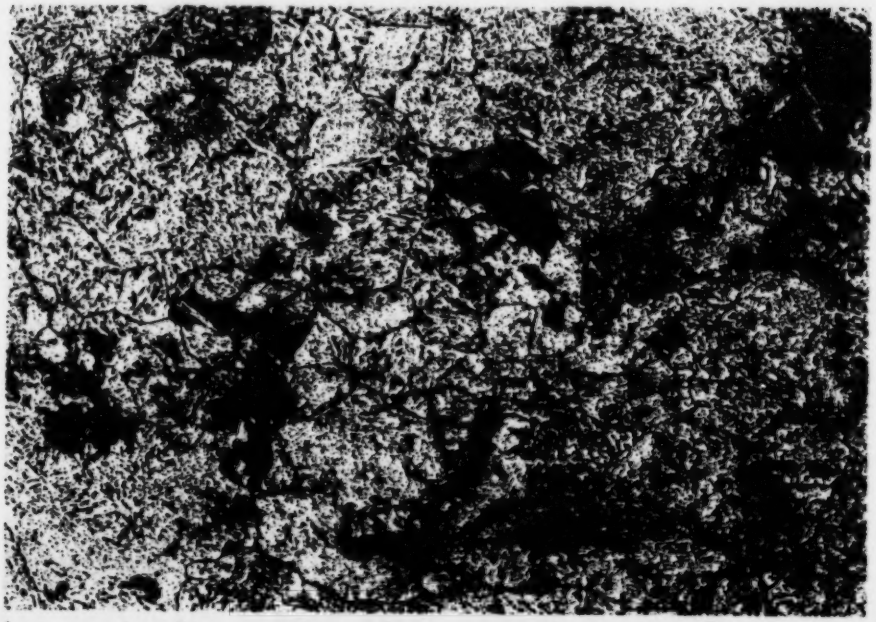
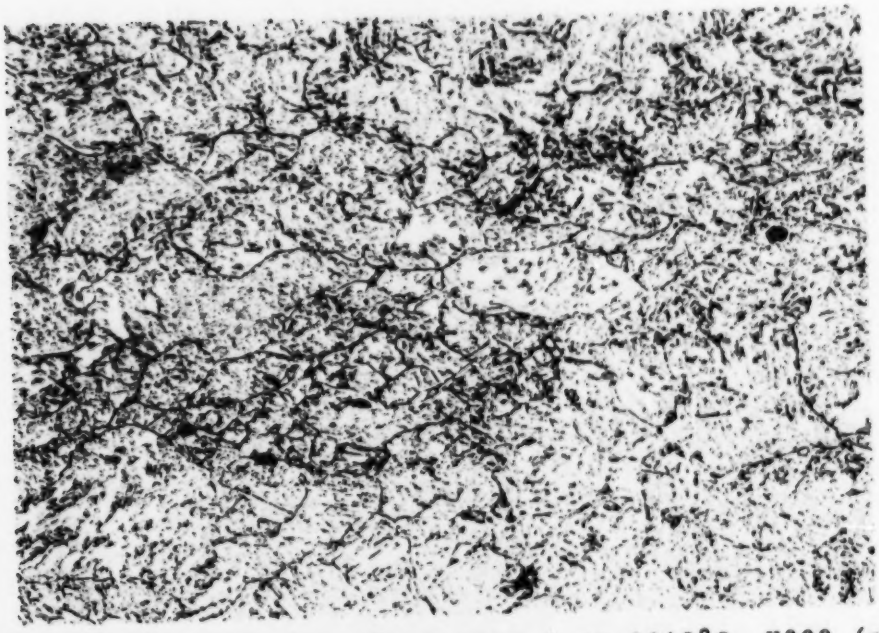


Fig. 2. Mixed austenite grain size in ingot rolled 1 pass of schedule 1. X75 (neg 7756)

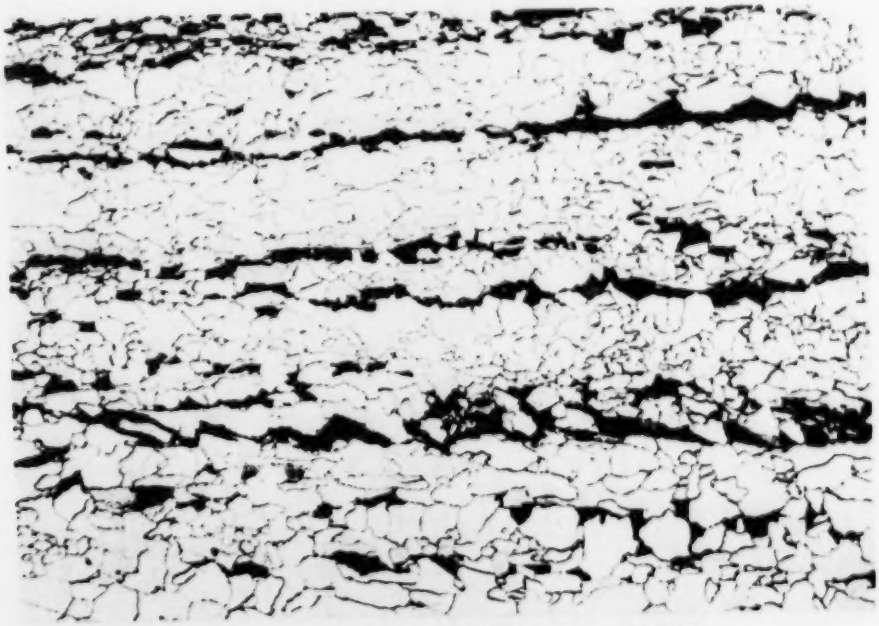
(a) Prior austenite grains in cylinder heated to 1230°C for 1 h in centre of dummy bullet. Note grains are more uniform in size than seen in Fig. 1. X50 (neg 7757)



(b) Prior austenite grains after pass 1 at 1150°C. X100 (neg 7758)
Fig. 3. cont'd.



(c) Prior austenite grains after pass 4 at 1040°C. X200 (neg 7759)



(d) Final plate microstructure. X500 (neg 7760)

Fig. 3. Grain refinament during schedule 2.